

# Etched Silicon Gratings for NGST

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# Etched Silicon Gratings for NGST

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## Abstract

We have developed the world's first etched silicon grisms at LLNL in September 1999. The high optical surface quality of the grisms allows diffraction-limited spectral resolution in the IR wavelengths where silicon has good transmission. We estimated that the scattering light level is less than 4% at 2.2  $\mu\text{m}$ . Silicon can significantly increase the dispersive power of spectroscopic instruments for NGST due to its very large refractive index ( $n = 3.4$ ). For example, a silicon grism with 40 mm clear entrance aperture and a  $46^\circ$  wedge angle can provide  $R = 10,000 - 100,000$  in  $\sim 1\text{-}10\ \mu\text{m}$ . The same grating working in the immersed reflection mode can provide  $\sim$  three times higher spectral resolution than in the transmission mode. To achieve a desired spectral resolution for NGST, the spectrograph size and weight can be significantly reduced if silicon gratings are used instead of conventional gratings.

## Introduction

The Next Generation Space Telescope (NGST) will open up a new frontier in astronomy. It will provide a new understanding of early universe, galaxy formation and evolution as well as nearby young star and planet formation and evolution. To achieve the potential scientific goals of NGST, it requires not only low dispersion spectroscopy, but also intermediate and high resolution spectroscopy. The gain in signal-to-noise ratio of NGST is approaching a factor of 1000 at spectral resolution range of  $R = 5 - 10,000$  over ground-based 8 m telescopes for wavelengths longer than 2.5  $\mu\text{m}$  (Gillet & Mountain 1997). Even at  $R \sim 100,000$ , the gain of NGST is still approaching a factor of 100 over ground-based 8 m telescopes (Carr & Najita 1997). It is relatively easy to achieve spectral resolution of  $R \leq 5,000$  with conventional gratings in NGST spectroscopic instruments in the near and middle IR (1-10  $\mu\text{m}$ ). However, it starts to push the instrument design to accommodate  $R > 5,000$  with conventional gratings since size and weight are the big factors for space mission. New technology is required to increase the dispersion power of the gratings used in the instrument without increasing the size of the instrument.

Immersion technology can help to improve grating dispersion power (e.g. Dekker 1988). The gain of the spectral resolving power would be the largest in the IR due to the availability of high-index materials such as Silicon ( $n = 3.4$ ) and Germanium ( $n = 4.0$ ). These would be perfectly matched with the NGST requirement for IR observations.

Silicon is of special interest because of its special crystal structure that allows anisotropic etching by certain chemical reagents, e.g. KOH, to generate V-shaped grooves on its surface to make a grating (Tsang & Wang 1975). Small gratings with very coarse grooves have been made on silicon wafers by several groups and have demonstrated good grating performance (Tsang & Wang 1975; Wiedemann et al. 1993; Kuzmenko, Ciarlo & Stevens 1994; Kuzmenko & Ciarlo 1998; Jaffe et al. 1998; Ge et al. 1999). However, no successful results have been reported on etched gratings on thick silicon disks. Because of the low transmission loss of the silicon material in the near and mid-IR (1.2 – 10.0  $\mu\text{m}$  and 20  $\mu\text{m}$  beyond) especially under cryogenic temperatures (Collins & Fan 1954), the etched silicon gratings can be operated in immersed reflection mode to increase the spectral resolving power by a factor of 3.4 over a conventional reflective grating of equal length.

The etched silicon gratings can not only be used in the immersion mode (silicon immersion echelle) to increase the resolving power, but also be operated in transmission mode (silicon grism) to increase the resolving power. For instance, the silicon grism can increase the spectral resolution by a factor of 6 over a grism made of  $\text{CaF}_2$  since the dispersion power of a grism is proportional to  $(n-1)$ . Therefore, the increased spectral resolving power with the silicon immersion echelle and grism are substantial; or the increased compactness of IR spectroscopic instruments with silicon gratings are significant at a given resolving power. Furthermore, very coarse grooves can be easily made through chemical etching technique for complete wavelength coverage on any focal plane array, while it is very challenging for traditional mechanical ruling technique to make very coarse grooves.

### **World's First Silicon Grisms**

We just developed the world's first silicon grisms in the state-of-the-art microfabrication facility at LLNL under the support of lab directed research and development funding in 1999. Figure 1 shows the silicon grisms with a mounted one in the middle. The grisms have 10x10 mm<sup>2</sup> etched area and 46° wedge angles. The groove spacing is 66  $\mu\text{m}$ . The detailed specifications of the silicon grisms are listed in Table 1.

The surface quality and roughness of these gratings have been tested at LLNL and show promising results. For example, the RMS wavefront error is 0.035 wave in reflection for the best silicon grating at 0.6328  $\mu\text{m}$ , corresponding to

Table 1. Specification of the silicon grating for the Lick 3m IRCAL camera

Material	Silicon
Operating temp.	$\sim 80\text{K}$
Grating wedge angle	$46.1^\circ$
Groove frequency	15.2 g/mm
Etched area	$10 \times 10 \text{ mm}^2$
Entrance Clear aperture diameter	5 mm
Spectral resolution	5,500 at K

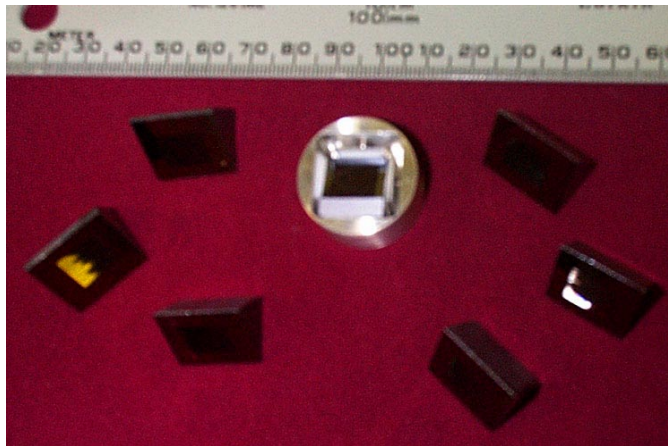


Figure 1. World's first silicon gratings made at LLNL. The middle mounted has been installed in the Lick 3m near-IR camera IRCAL for initial testing in the end of October 1999.

0.027 wave in transmission at 1.0  $\mu\text{m}$  (Figure 2). This RMS wavefront quality will enable the grating to provide diffraction-limited spectral resolution in the IR. The RMS surface roughness has also been measured, and is  $\sim 50 \text{ nm}$  for the best gratings. The corresponding diffuse scattering is estimated to be less than 4% at K band for these silicon gratings with silicon nitride AR coatings. The overall optical performance meets the design requirement for scientific observations.

One of the silicon gratings has been installed in the Lick 3m near-IR camera IRCAL and will be tested with starlight in the end of October 1999. With a 5 mm diameter pupil size of the IR camera, this grating will potentially provide  $R = 5,500$  with a 0.2" slit in the K band. With a  $\text{CaF}_2$  grating, fabricated by the

Hyperfine Inc., as the cross disperser, ~ 10 orders of spectrum, or the whole K band, will be covered by the 256x256 HgCdTe array. Figure 3 shows the expected spectral format in the IRCAL camera. Other silicon grisms with silicon nitride AR coatings and different wedge angles along with the  $\text{CaF}_2$  grism will be tested in the lab later this year. The lab measurements show that the nitride coatings can provide an average of 97% transmission for the grism in the K band, while bare silicon without coatings can only transmit 54% IR light. The detailed testing results will be presented at a later meeting (Ge et al 2000).

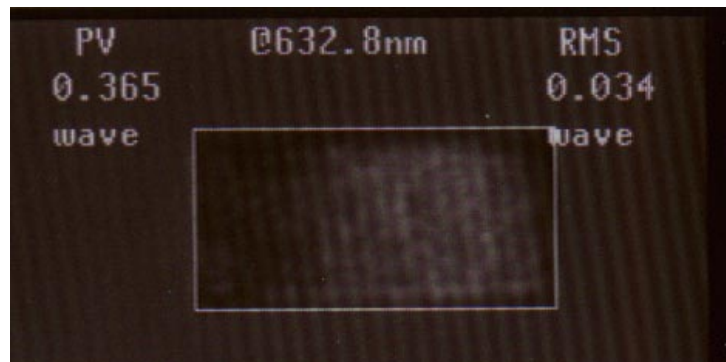


Figure 2. RMS wavefront error on the best silicon grism. It is measured in the reflection at 0.6328 nm with a Zygo interferometer at LLNL.

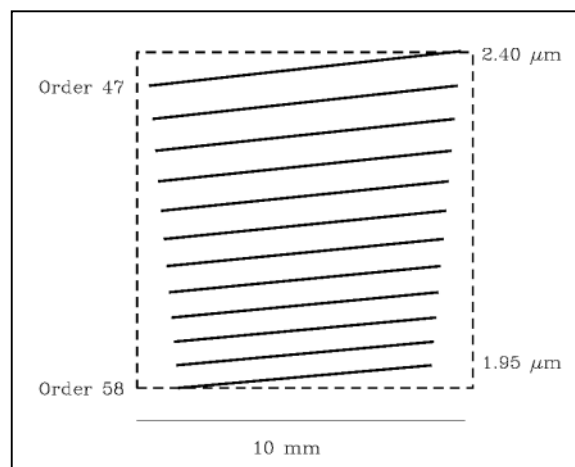


Figure 3. Spectral format of the silicon echelle grism mode in the IRCAL camera at  $R = 5,500$  in the K band. Cross-dispersion is provided by a  $\text{CaF}_2$  grism. The dotted line box is the physical size of the 256x256 HgCdTe array.

### Development of Large Silicon Gratings

We continue the development of etched silicon gratings at LLNL in FY00

with the goal to make a prototype silicon immersion echelle with etched area of about  $100 \times 50 \text{ mm}^2$  and blazed angle of  $63.4^\circ$ . In order to achieve this goal, new equipment will be installed for reducing the roughness of the etched grating facets. These new equipment include ultrasonic and endpoint detection system. New techniques will be applied in the etching procedures to improve surface quality of the etched gratings over large area and reduce overetching and nonuniformity. These new techniques include new photoresist coatings for thick, heavy silicon disks, endpoint detection, and selective etching.

Once the large silicon gratings can be developed, they can be potentially implemented in NGST spectrographs and cameras to increase spectral dispersion power within the fixed volume for these instruments. For example, a silicon grism with  $\sim 60 \times 40 \text{ mm}^2$  etched area and a  $46^\circ$  wedge angle will be able to provide a diffraction-limited spectral resolution  $R \sim 40,000$ ,  $20,000$ , and  $10,000$  at  $2.5 \text{ }\mu\text{m}$ ,  $5.0 \text{ }\mu\text{m}$  and  $10 \text{ }\mu\text{m}$ , respectively. Higher resolution can be achieved with a grism with a larger wedge angle, or camera pupil size larger than  $40 \text{ mm}$ . The same silicon grating, working in the immersed reflection mode for a NGST spectrograph, will be able to provide  $R \sim 100,000$ ,  $50,000$  and  $25,000$  for  $2.5 \text{ }\mu\text{m}$ ,  $5.0 \text{ }\mu\text{m}$  and  $10.0 \text{ }\mu\text{m}$ , respectively. This new spectral resolution capability with the NGST can be achieved at the cost of only the grating fabrication and implementation.

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